# Project SOCRATES: A New Sensor Technology for Enhancement of Aviation Safety and Capacity

**by**

**William Cotton, Flight Safety Technologies**

**for presentation at**

**The 2002 FAA Airport Technology Transfer Conference**
**May 5-8, 2002**

## Introduction

Project SOCRATES is an applied research and development program aimed at exploiting sensing and processing technologies previously developed for military applications. The project objective is enhanced air safety and airport productivity, through remote, long-range detection of potentially hazardous atmospheric phenomena, using the previously untried sensing domain property of acoustics. Potential air safety applications include both ground-based and airborne systems for detecting and warning of such hazardous conditions. Airport productivity would be improved by changing the rules for separating aircraft from wake turbulence to reflect the measured location of these wakes.

## 1. History and Objectives

At the end of the cold war, many technologies developed for military applications were de-classified and applied to worthwhile civil applications. One such technology involved the use of laser beams to sense sound. In 1997 an investigation was started into the use of this and various signal processing techniques to detect atmospheric disturbances that create hazards to flight. These hazards are both naturally occurring and manmade. Strong convective turbulence and microbursts associated with thunderstorms have long posed a danger to aircraft through performance degradation and loss of control during penetration of these areas. In some cases even structural failure has occurred. Conventional airborne and ground-based radar protect against most of these encounters but in a very dry air mass, radar cannot detect them. Similarly, the wind shear hazard known as clear air turbulence is not detected by radar since, as its name implies, the clear air environment does not provide sufficient reflectivity for conventional radar to function.

The man-made atmospheric hazard to aircraft known as wake turbulence is caused by the creation of lift from wings or rotors, and remains in the path behind the generating aircraft for up to several minutes. Wake turbulence is characterized by two parallel vortices rotating in opposite directions and trailing behind and drifting below the aircraft that creates them. While all aircraft continuously generate vortices while in flight, their strength, and therefore the danger they pose to following aircraft, is a function of the weight, speed, and wingspan of the generating aircraft. The heavier, the slower, and the shorter the span, the stronger is the vortex. Thus large transport airplanes flying slowly near airports pose the greatest hazard. The persistence of the vortex is determined by the stability of the atmosphere. In a very stable “smooth” air mass, the natural decay of the vortices may take up to two or three minutes. Air traffic authorities have mitigated this hazard by applying procedures to separate aircraft by increased distances and times according to their weight categories to allow sufficient time for vortex dissipation. These procedures provide the greatest separation to light aircraft following heavy ones, as this combination poses the greatest risk.

The wake turbulence separation procedures have proven to be quite safe over the years, but some concerns remain. During visual flight conditions, pilots provide their own wake separation with no means to measure the distance between themselves and the location or the persistence of the vortices they are trying to avoid except through estimation based on the observed position of the generating airplane. Also, there are some conditions in which the air traffic procedures being applied may be inadequate and still permit a vortex encounter to occur.

In addition to the danger posed by wake vortices, the avoidance procedures themselves are wasteful of scarce airport capacity through the extra spacing provided between airplanes. This extra space reduces the number of airplanes that can take off or land during an hour, quite significantly when a mix of aircraft types is using the airport. While the safety of these flight operations will always be paramount, it has long been recognized that the vortices do not normally pose a flight risk even at normal spacings between airplanes because they are either transported out of the path of the following aircraft by the wind or broken up by ambient turbulence before the next aircraft gets there. Accordingly, there has been a great deal of effort during the last three decades to devise means for both improving the operating safety in the presence of wake vortices and to regain the capacity lost to current procedures whenever it is safe to do so. A practical system for accomplishing this has not been forthcoming for several reasons, chief among them is the lack of a system for reliably measuring the position and strength of the vortices in real time to verify predictions made of their behavior.

After years of research during the 1970s, a system was devised for use at Chicago’s O’Hare airport that provided air traffic controllers with an indication whether they needed to apply wake turbulence separation standards, or not. This system’s output was based upon wind measurements made at the surface near the landing runway threshold. If the wind showed that lateral transport of the vortices was sufficient to eliminate the risk to following aircraft, a green light was given to the controllers to use normal spacing. This vortex avoidance system was not adopted because of pilot’s concerns that the wind might be sufficiently different above the ground to permit the hazard to be present even if it was not near the surface. The controllers also did not like the guidance switching back and forth during marginal conditions, interrupting the stable flow of traffic.

In the early ‘90s, NASA conducted a program called AVOSS, for Aircraft Vortex Spacing System. This research advanced the science of vortex behavior and proposed a system for arrivals that checked the vortex position in a number of windows along the approach corridor. The AVOSS was designed as a predictive system but used a Lidar to confirm the predicted positions of the vortices in the approach windows. Discussions with aviation system users, most notably the pilots, again pointed to the desire to have confirmation of the predicted vortex behavior during all operations.

While lasers attenuate very rapidly in clouds and fog, sound waves do not. Therefore, the SOCRATES project has focused initially on the application of opto-accoustic technology to the problem of wake vortex localization and tracking under all weather conditions. If successful, it is proposed as an element of a Wake Vortex Advisory System (WVAS) to be used in air traffic control to improve the safety of operations and to benefit the capacity of the airports where it is used as well.

The current SOCRATES research is sponsored by the FAA and NASA, with the DOT's Volpe - National Transportation Systems Center as the project control agency. Flight Safety Technologies of New London, CT is teamed with Lockheed Martin's Naval Electronics and Surveillance Systems of Syracuse, NY for technology development, demonstration, and evaluation.

## 2. Technology Description

The technical basis of SOCRATES is application of an optical sensing system to detect acoustic energy. General Electric invented this form of opto-acoustic sensing in the late 1960s. Application to air safety relies on two premises. One, the atmospheric hazard emits sound of sufficient strength (loudness) and with distinctive spectral, temporal and spatial characteristics. Two, the opto-acoustic sensors can be configured to detect and localize the emitted sound at sufficient range to permit timely warning. The validation of these premises is the goal of Project SOCRATES.

The basic sensing system concept consists of an array of opto-acoustic sensing beams located on the ground. Sound emitted by hazardous conditions propagates through the atmosphere to the opto-acoustic sensors, where it is detected. Processing of the detected signals from each opto-acoustic sensor in the array of sensors is used to localize and characterize the hazard. Figure 1 depicts the heterodyne interferometric implementation for opto-acoustic sensing. The interaction of propagating acoustic signals with the optical beam in the "sensing region" creates modulation of the index of refraction that is manifested as a phase modulation of the optical beam, which can be detected at extremely low levels using conventional FM demodulation techniques.

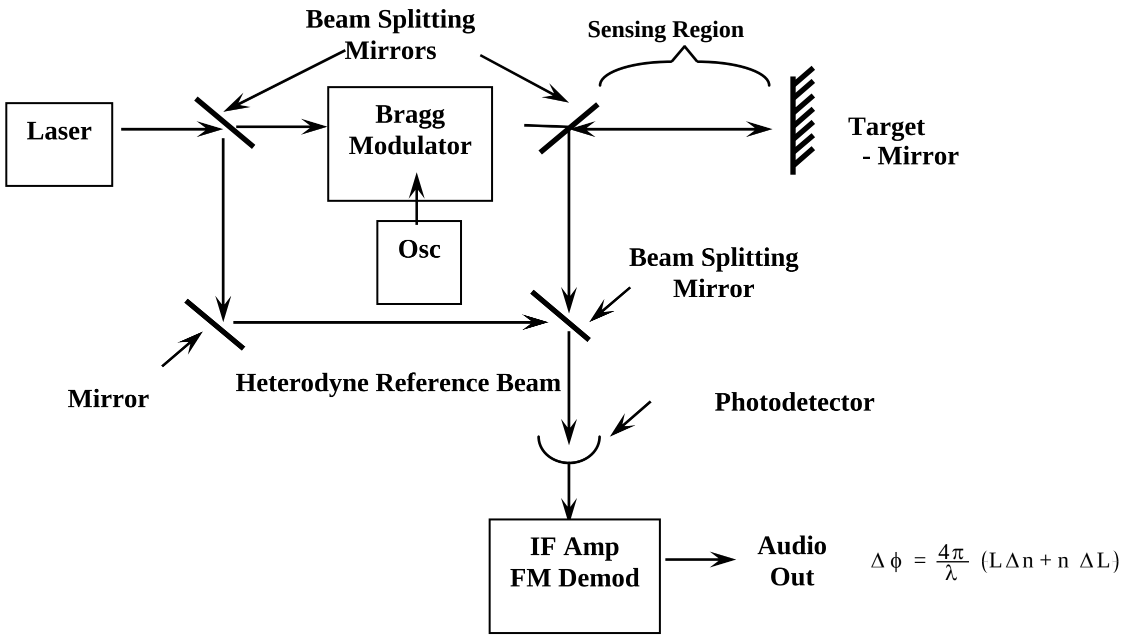



Figure 1. The Opto-Acoustic Sensing Optical Heterodyne Interferometer Implementation.

The basic advantage of this concept is that a single optical beam of very long length (up to kilometers) replaces a large number of conventional microphones to achieve the same directional response. This discriminates against interference from acoustic sources that are not normal to the optical beams. Use of a retroreflecting mirror for the "target" enables use of low power for the optical beams, about 5 mwatt average power. This low power, an "eyesafe" wavelength, and beams confined to the ground greatly mitigates eye safety concerns.

A testbed system with two 100m long optical sensing beams was developed and deployed at JFK Airport in May, 1998 for detection of aircraft wake vortices during landings. Subsequently a four-beam testbed was developed at deployed at Langley Air Force Base in December, 2000 for detection and tracking of aircraft wake vortices from a Boeing 757 in level overflights (but in a landing configuration) at various altitudes. The basic testbed configuration is shown in Figure 2. Most optics, electronics, processing, and display are contained in a small rack within the trailer. Fiber optic cable takes the optical pulses to the Transmit/Receive Module (TRM) where approximately 4% of the light is reflected back as a reference pulse while the remainder is expanded and collimated to a diameter of about 2.5 cm and transmitted along the "sensing region". The light pulse is reflected back along itself at the retroreflector and received at the TRM, which focuses it back into the optical fiber and back into the trailer. The acoustic signal of interest modulates the phase of the light in its transmission along the path from the TRM to the retroreflector and back. This phase modulation is then demodulated via electronic processing within the trailer to recover the acoustic signal of interest. Subsequent spectral, temporal, and spatial processing is used to enhance signal-to-noise and for localization.

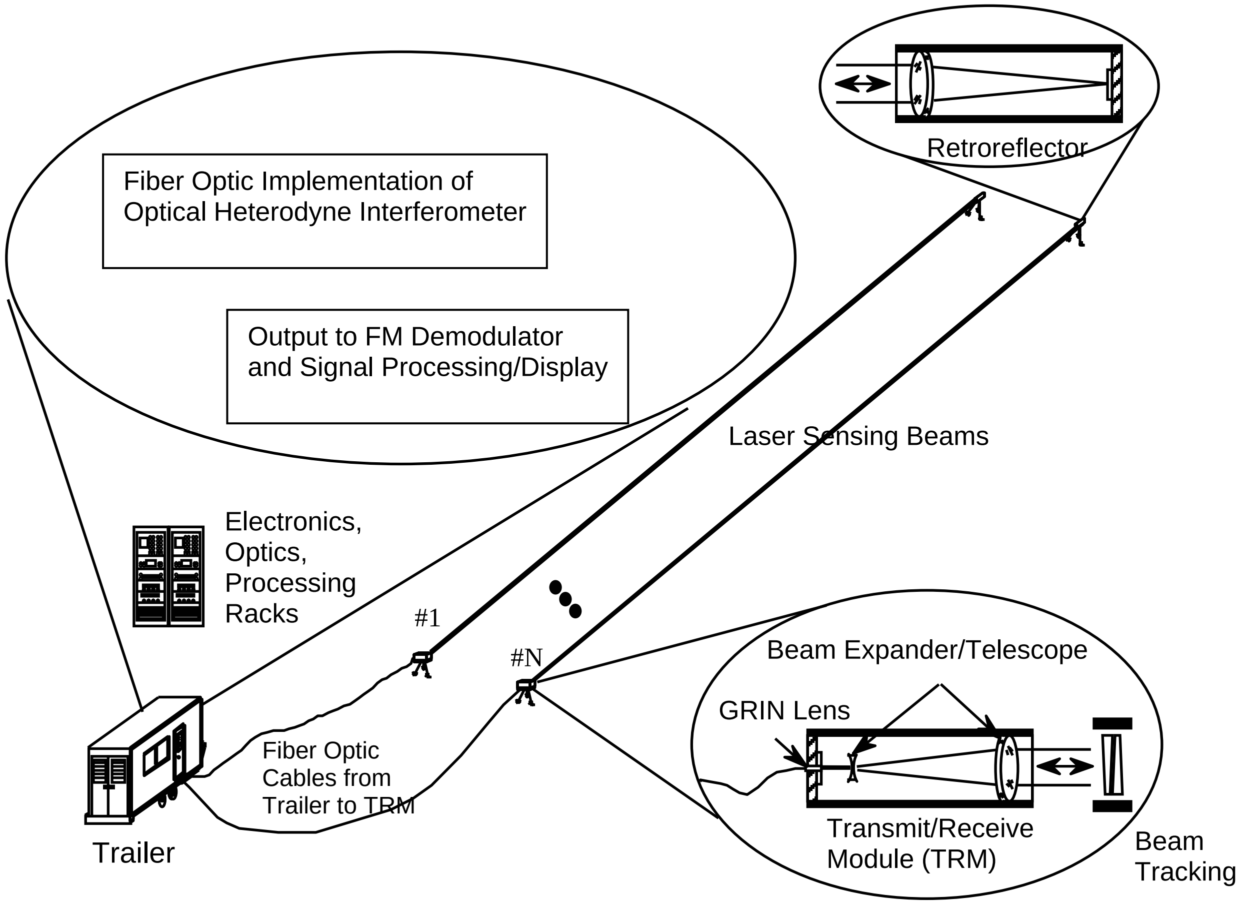



Figure 2. SOCRATES Testbed Configuration.

## 3. JFK and Langley AFB Test Results

### JFK Airport

The initial two-beam testbed system was deployed near the Middle Marker of Runway 31R at JFK Airport in May, 1998. Over a 10-day period various configurations of the two beams were deployed to collect data on wake vortices from landing aircraft. The aircraft altitude at the position where they flew directly over the sensing beams was about 70m. JFK testing resulted in the collection of data from over 400 aircraft larger than business jets under the various sensing beam configurations and atmospheric conditions. The test site also contained the Volpe Wind Line to provide independent verification of wake vortex location. Figure 3 depicts the signal outputs from each of the beams in an orthogonal configuration. As predicted, Beam 1 detected the aircraft noise well before Beam 2 due to the spatial response characteristic of the long sensing region. The output decays rapidly after “fly-over” until the aircraft has landed and the thrust-reversers are engaged. The time region from 5-20 seconds after “fly-over” is the period where the wake vortex acoustic signal can be detected.

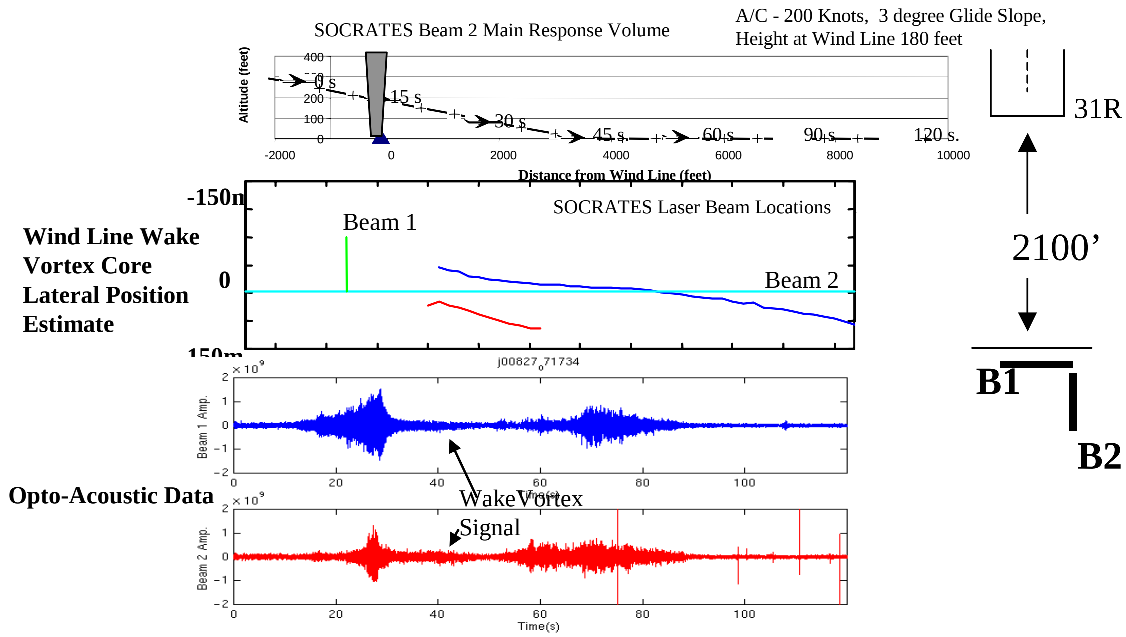



Figure 3. SOCRATES Wake Vortex Data from Two Beams at JFK.

Figure 4 confirms this detection by tracking the wake vortex elevation angle and comparing the track to that of the Volpe Wind Line.

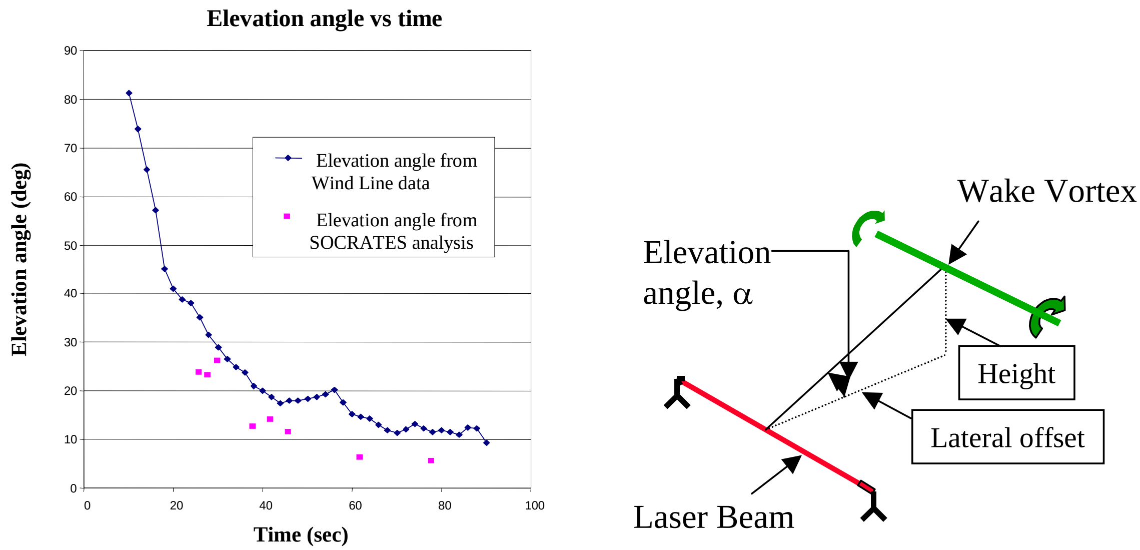
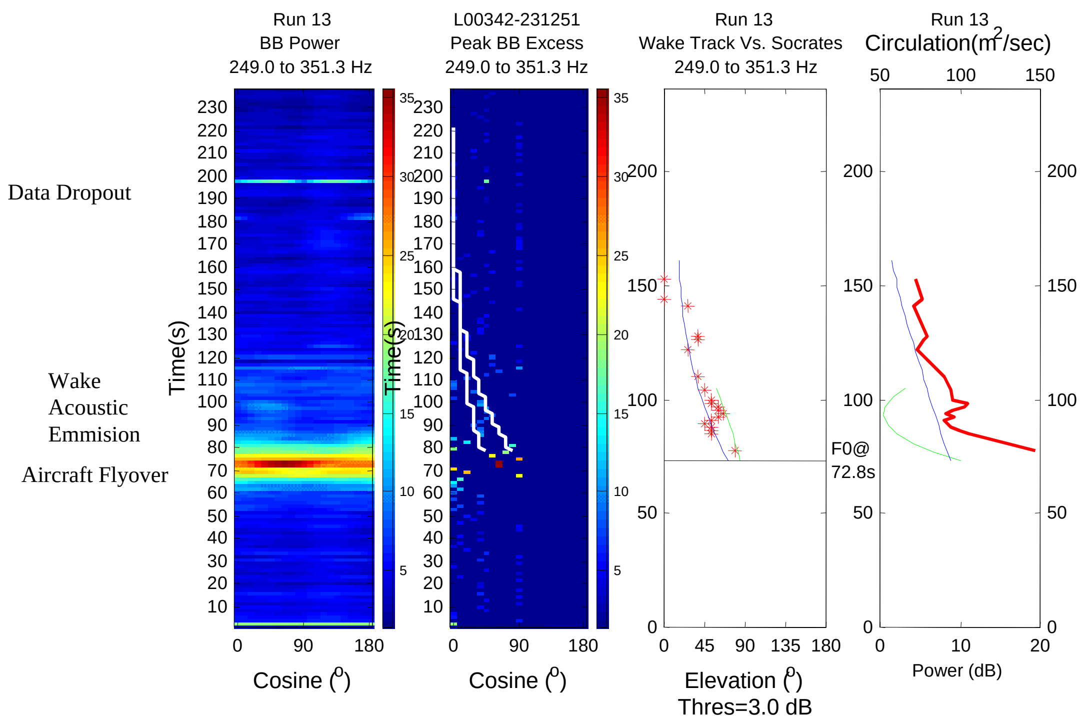



Figure 4. SOCRATES Wake Vortex Elevation Angle Tracking Compared to Wind Line from JFK.

These results demonstrated that aircraft wake vortices do generate sound and that the opto-acoustic sensing technology detected the radiated sound.

Langley Air Force Base

The four-beam testbed system was deployed at Langley Air Force Base (LAFB). NASA's Boeing 757 aircraft was used to provide more controlled conditions. The aircraft performed level flights at altitudes ranging from 75m to 170m over the SOCRATES array, with the aircraft configured for landing. Twenty-two overflights were made on four days during our 9-day deployment period. The four SOCRATES beams were parallel to the runway, about 80m from the runway centerline, and separated from each other by about 0.5m for all runs. Data were recorded by the SOCRATES system on 19 passes. NASA Lidar recorded simultaneous data on 13 passes. Figure 5 depicts the SOCRATES results from beam forming the four SOCRATES sensing beams, with detection of the wake vortex acoustic signature (panes a and b) and comparison of the SOCRATES detection track with the Lidar track (pane c). Pane d compares the Lidar estimate of wake vortex circulation with the SOCRATES acoustic signal level.




(a) (b) (c) (d)

Figure 5. SOCRATES Wake Vortex Detection, with Lidar Comparison, at LAFB.

The overall detection results were 17 wake vortex detections out of the 19 opportunities. The two missed detections occurred on days with gusty wind conditions, which are known to increase the background noise level of the air beam opto-acoustic sensors. The results from LAFB also verified that wake vortices emit sound even when they are out of ground-effect, which they never were during the JFK test.

The JFK and LAFB tests were the first measurements dedicated to collecting data on the acoustic characteristics of sound generated by wake vortices. In general the signals appear to be broadband in nature, with most energy in the 100 to 1000 Hz frequency range. The SOCRATES sensor currently has response up to 5000 Hz, but is very noisy below about 100 Hz.

## 4. Concept of Operations and Summary of Operational Benefits

The NASA and FAA-sponsored research to date has made it possible to describe a system to determine the presence or absence of the wake vortex hazard. This system, which is now called the WVAS, would provide air traffic controllers with information for the safe spacing of aircraft on approach or departure while re-capturing most of the capacity lost to current vortex spacing procedures. The WVAS information will be available to controllers in each of the operating scenarios that is addressed by current air traffic control wake turbulence procedures – single and dual arrivals, single and dual departures, crossing runway operations, and airborne crossing operations.

The WVAS will perform its function by predicting vortex behavior and assessing its hazard from each aircraft to any other that may be affected. At critical points on the flight path, measurements of actual vortex behavior are made and compared to the predictions for confirmation of WVAS output and possible alerting if, for any reason, the actual vortex behavior presents a possible hazard when it was not predicted to do so.

The SOCRATES wake vortex sensor is intended to be used for the tracking component of the WVAS. Atmospheric sensing would be used for an initial prediction of the presence or absence of the hazard to a following aircraft, based on vortex transport or dissipation behavior. This function would be provided by wind profiler measurements and METCARS wind and turbulence data sensed on board the aircraft and transmitted to the WVAS by data link. The WVAS processor would also receive surveillance information on the tracks of the aircraft being protected from normal ATC surveillance sources. These three kinds of information, aircraft surveillance, wind and turbulence measurement, and vortex tracking data would be used to provide controllers the WVAS outputs.

One of the WVAS outputs is vortex spacing status – an indication of whether the extra space behind heavy aircraft must be provided or not. The other output that might rarely occur is a specific aircraft alert for which vortex spacing safety is about to be compromised. If an alert is given, the controller would take action to separate the effected airplane from the potential wake encounter. These outputs would be given to both TRACON and Tower local controllers who are responsible for establishing wake turbulence spacing between aircraft.

To perform the function envisioned for a Wake Vortex Advisory System, the following basic requirements should be met:

- All available runway capacity should be made available for both landing and departing traffic. This means that runway occupancy becomes the limiting factor when the WVAS shows that the vortex hazard is not present.
- The WVAS must provide for stable arrival traffic flow. This means that once an arrival flow rate is established for an airport based upon no vortex hazard being present (nominal separation), the system cannot flip back and forth between nominal spacing and wake vortex spacing, causing delays to back up into the arrival stream or aircraft to be pulled out of

landing sequence. The stability of the arrival flow rate should be forecast for approximately 30 minutes (actual value TBD).

- The WVAS must ensure no hazardous wake encounters. During normal operation of WVAS, the system integrity must be sufficient to provide a probability of a hazardous vortex encounter that is lower than under existing procedures. Combining predictive, measurement, and alerting techniques may achieve this requirement.
- The WVAS should be operative and effective during all weather conditions when flight operations are being conducted.
- The WVAS must directly measure the vortex behavior in ground effect as well as at the most critical part of the arrival and departure path. This is the stabilized approach point for arrivals and the first four hundred feet of climb for departures.
- The outputs of the WVAS to the responsible air traffic controllers should be:
  - Integrated into existing and planned controller workstations.
  - Intuitive in the information presented, not requiring further analysis or cross-referencing to determine actions to be taken.
  - Visual in normal presentation, in the primary field of view.
  - Aural, as well as visual, when presenting "alert" information.

The prediction from the WVAS that the vortex hazard will not be present would be based on one of three possible mechanisms for removing it from the flight path of the following aircraft. These are:

- Dissipation - the strength of the vortex has decayed to the point that no hazard is presented to the airplane encountering it. (See Figure 6-1)
- Transport - the vortex has been transported by the wind to the side of the flight path of a following airplane, or not into the path of an airplane on an adjacent approach or runway. (See Figure 6-2)
- Vertical separation - the vortex is below or above the path of the following airplane. This must be a known and "navigated" path, such as a glide slope, or fixed altitude being maintained.
  (See Figure 6-3)

These mechanisms have been presented in a single approach "following" scenario. The departure scenario can only use the dissipation or lateral transport mechanisms for vortex removal as the vertical flight profile of a departing aircraft is performance-based and cannot be known in advance. When runways are very closely spaced (less than 2500 feet apart), the runways are said to be "vortex dependent" and are treated as a single runway for wake turbulence purposes. The WVAS approach to such "dual" runways is to check for transport from one approach or departure path to the other, in addition to the single along-track case. Again, during departures, the vertical separation mechanism cannot be used.

When crossing runways are used, the location of the intersection will determine whether it is possible for airplanes using both runways to be airborne over the intersection. When such is

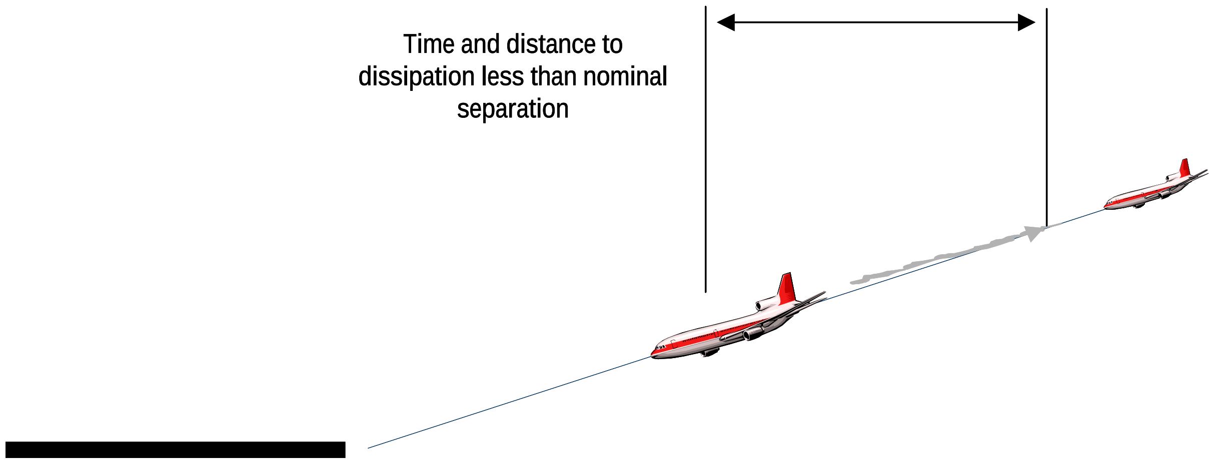



Figure 6-1 Dissipation Mechanism

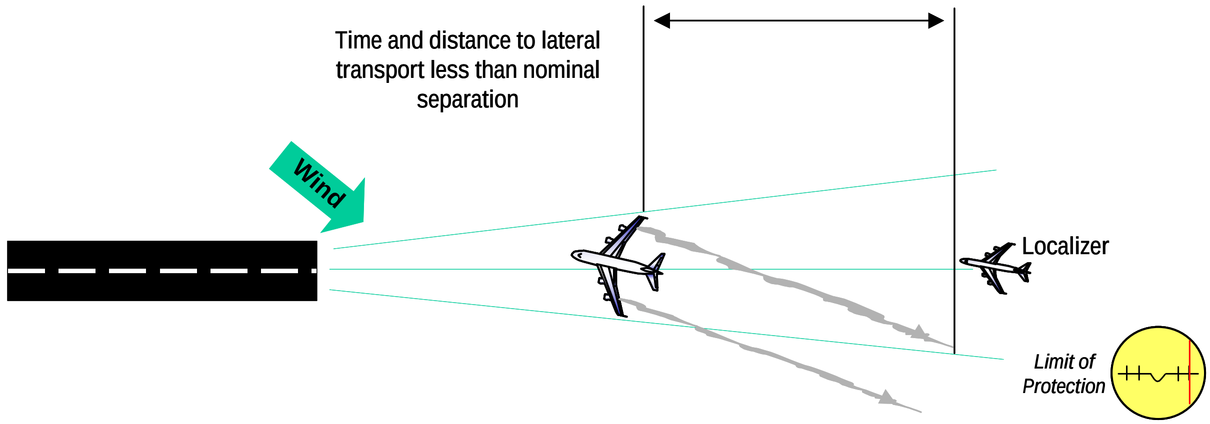



Figure 6-2 Lateral Transport Mechanism

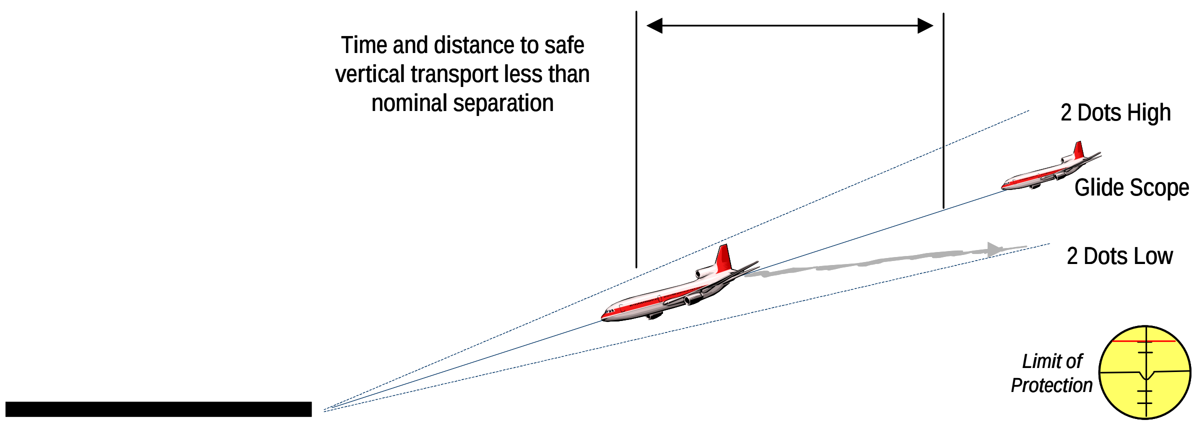



Figure 6-3 Vertical Transport Mechanism

the case, WVAS would use the dissipation or transport mechanisms to determine presence or absence of a hazard. There are a few locations where flight paths to runways at different airports cross at low altitude. Any of the three mechanisms may be used to evaluate the risk in the airspace near the crossing point.

The WVAS holds the potential for providing very substantial benefits at every airport used by multiple wake categories of aircraft. Most significantly, pilots will have a backup to their judgments regarding safe separation from the wakes of the airplanes they follow or fly alongside. Every close operation will have an automated system ensuring a very low risk of wake vortex encounter. When the number of flights increases in the future and the mix of categories at an airport increases with more heavies, including the new A-380 and lots of small jets added to the fleet, the value of WVAS to maintaining safe operations goes up exponentially.

The capacity gained through implementation of WVAS will allow the runway acceptance rate once again to be governed by runway occupancy times, not terminal area or final approach wake vortex spacing. The capacity gained at any one runway will be dependent on the traffic mix, the airport configuration, and current operational procedures; however, the changeover in capacity limiting factors will fundamentally improve the approach capacity equation. On departure, the introduction of noise abatement routes that are flown using Flight Management Systems is already altering departure capacity for many runways in all weather conditions. These procedures, when coupled with current wake vortex separation requirements, negatively impact the departure capacity of the affected runways. WVAS implementation will maximize the recapture of the capacity lost through the introduction of these new noise procedures.

Most of the time, WVAS will permit the maximum capacity of a runway to be realized without applying the current artificial limitation of wake turbulence spacing criteria. This has the effect of treating all categories of aircraft as if they were small. Instead of using four, five, or six miles of separation between airplanes of different weight categories, all could be provided with three. The most noticeable effect of this is delay reduction as airplanes may be safely brought in closer together which, in turn, allows the airport to more easily accommodate the schedule. When the B-757 was given its own wake category, requiring an extra mile be provided to other large airplanes following it, the delay impact was immediate and dramatic. WVAS could provide just as dramatic a decrease in delays.

The benefit of successful use of SOCRATES in a WVAS is its all-weather capability and the ability to sense vortices at rather large distances. Theoretical analysis of a focused multi-beam array shows the promise of reliable detection of dangerous vortices from several miles away and the ability to localize with sufficient accuracy to perform the functions described above. It is still necessary, of course, to prove out this capability through field trials of the more capable SOCRATES design.

## Conclusion

Results to date indicate that SOCRATES has promise to provide remote, long-range, eyesafe detection of aircraft wake vortices. However, additional development efforts remain to reduce sensor system noise levels, improve detection tracking, and validate localization concepts. Future plans include upgrades with more optical sensing beams in array configurations for improved detectability and localization capability. This improved system would again be tested at an airport for wake vortex detection and also for other atmospheric phenomena that may represent a hazard to aircraft operations. The application with the greatest near-term benefit from SOCRATES use is a sensor for the NASA/FAA developed WVAS. A successful implementation of the WVAS would dramatically improve both safety and efficiency of airport and terminal operations at precisely those locations that need these benefits the most.